Particle Accelerators, 1971, Vol. 2, pp. 1–11

PROGRESS REPORT ON THE NAL ACCELERATOR

F. T. COLE

National Accelerator Laboratory,† *Batavia, Illinois, U.S.A.*

Progress is reviewed on the proton synchrotron under construction at the National Accelerator Laboratory. The components of the accelerator are given brief descriptions and their present status is presented.

1. INTRODUCTION

All hands at the National Accelerator Laboratory are giving maximum effort to achieve the scheduled beam date of July, 1971. Almost all aspects of the accelerator design are fixed, and it is perhaps appropriate at this time to review the design and the construction progress of the project.

Informal discussions of the next step in energy began even before the CERN PS and Brookhaven AGS were completed and brought into operation in 1959 and 1960. In 1963 the Ramsey Panel recommended the construction of a 200-GeV proton synchrotron to the U.S. Government. A design study was carried out at the Lawrence Radiation Laboratory, Berkeley, reporting in 1965.[(1)] A design study was also carried out at CERN for a 300-GeV synchrotron.[(2)] Some features of the NAL design have carried over from these studies.

The United States Atomic Energy Commission studied the many sites proposed for the accelerator and chose the present site, 30 miles west of the center of Chicago, in December, 1966. The land, 6800 acres, was purchased from private owners by the State of Illinois and presented to the AEC for the Laboratory.

The Laboratory staff began to form in early 1967 and assembled in rented quarters near the site on June 15, 1967. The main features of the design were settled in a very short time and a design report written.[(3)] The first NAL group, the Linac Section, moved to the site early in 1968, making use of the homes in the former village of Weston for temporary quarters, and the remainder of the Laboratory was on the site by October, 1968. Ground was broken for the first permanent structure, the Linac Building, on December 1, 1968. The first contracts were let for accelerator components in July, 1969.

In the sections below, we shall outline the design of the major systems and then review the present construction status.

2. ONCE OVER LIGHTLY . . .

Figure 1 is a simplified layout of the accelerator and other parts of the Laboratory on the site. The first step in the acceleration process is a 200-MeV linear accelerator. Its design has been done in close collaboration with the Brookhaven and Los Alamos groups. The postcoupler system originated at Los Alamos is utilized in all tanks except the first. A description of the design and operation of the 750-keV preinjector and 10-MeV first tank has

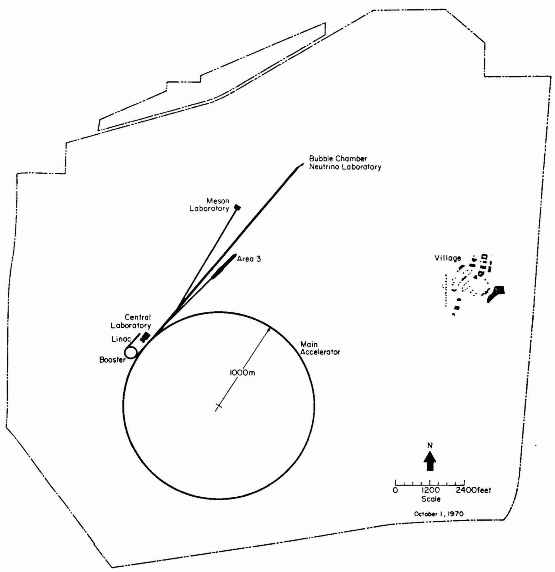


FIG. 1. General plan of the site.

† Operated by Universities Research Association Inc. Under Contract with the United States Atomic Energy Commission.

been published in this journal,[4] and we shall not discuss the linac in detail in this report.

At 200 MeV the protons are injected into the booster, an 8-GeV rapid-cycling synchrotron. Twelve successive pulses of 8-GeV protons accelerated by the booster are injected into the main accelerator while its guide field is held constant. After injection, the protons are accelerated to full energy, extracted, and transported to the experimental targets.

The design of these separate parts of the whole accelerator system will be discussed below in more detail. Let us first dispose of some general comments about the design.

The idea of using a booster synchrotron as injector for the main accelerator is not new. It was suggested by Wilson[5] and later proposed by Sands.[6] Boosters were proposed in both the LRL[1] and CERN[2] design studies.

An injection energy of several GeV into the main accelerator is needed to minimize distortions caused by remanent fields and to afford a reasonable space-charge capability. A linear accelerator of several GeV energy would cost more and give a lower space-charge limit in the main accelerator than the combination of a shorter linac (up to about 200 MeV, where the shunt impedance of the Alvarez structure begins to fall off significantly) and a booster of approximately 8-GeV energy. The decision to utilize a booster was made in the earliest days of NAL. In order to avoid the difficulties of complex magnets in a multiple ring[7] or decaturn extraction in a slow booster, we chose the simplest concept, a rapid-cycling booster.

With booster injection, a large ring is capable of intensities in the range of 10^{14} protons per pulse. Use of such high intensities with internal targets would lead to very difficult radioactivity problems. We have, therefore, planned from the outset to rely completely on external beams for physics experiments (except for some preliminary experiments incidental to putting the machine into operation, which will be done at very low intensities). Two of the most important developments of synchrotrons in the last decade aid considerably in the achievement of good-quality, high-efficiency external beams. These developments are the long straight section[8] and the electrostatic septum.[9] Together, they form the basis of a resonant slow-extraction system whose theoretical efficiency is well over 99%.

Finally among these general comments, the chronology sketched above shows that several years elapsed while the accelerator was being studied and the site chosen. There was a consequent concern that the parameters chosen in 1963 might not be those most desired in 1972, the original date for initial operation of the accelerator. In an attempt to meet these problems, we built as much flexibility as we could into the design. It will be possible at a later time to increase the beam intensity, the number and size of the experimental areas, and to add a beam bypass and storage rings. But by far the most important option built in was for a later increase in energy above 200 GeV. This option has already been exercised, and we are now building a 500-GeV accelerator.

3. THE MAIN ACCELERATOR

The main accelerator is a separated-function synchrotron with six long straight sections. Its equivalent radius is 1000 meters (giving a circumference of 20614 feet or 3.9 miles).

The concept of the separated-function synchrotron is not new, but dates from the early days of alternating gradients. It was proposed by White[10] in 1953 and independently by Kitagaki,[11] and its theory extensively developed at Princeton.

The separated-function design has several advantages. In a combined-function magnet, the field at the high-field side of the aperture is larger than the field on the central orbit by a factor $(1+ka)$, where k is the relative gradient B'/B and a is the half-aperture. For the ordinary run of parameters, ka is approximately 15 to 20%. When the gradient (k) is zero, it is, therefore, possible to achieve central-orbit fields that are higher by this 15 to 20% for the same peak field somewhere in the aperture, a particular advantage in a very large synchrotron.

Second, the focusing is more efficient because the focusing quadrupole is at the point of the maximum of the amplitude function β, thus having most focusing effect, while the defocusing quadrupole is at the point of minimum β, thus having a small defocusing effect. The total gradient length of the NAL main accelerator is 60% smaller than that of the combined-function LRL design,[1] while the radius is only 30% larger.

Third, there is a flexibility in the separated-function structure that can be very useful. The excitation of the quadrupoles can be adjusted relative to that of the bending magnets, thus adjusting the ν-values. We plan to use this to reduce the peak gradients; in a 500-GeV cycle, we will adjust the quadrupole excitation to produce ν-values of approximately 16.25 instead of the nominal 20.25. The amplitude functions are increased only about 10% by this change, giving amplitude increases of only 5%.

The choice of exactly 1000 meters for equivalent radius is to some extent arbitrary, within the constraints of attainable peak fields and the maximum energy desired. One could, in principle, investigate the variation of cost with radius within these constraints. But the cost minima found in accelerator design are usually so broad that it is entirely possible to spend more money investigating the minimum that it can save.

The Lattice

Figure 2 shows the main-accelerator lattice. The accelerator has six superperiods, each with 14 normal cells, one long straight section, and one medium straight section.

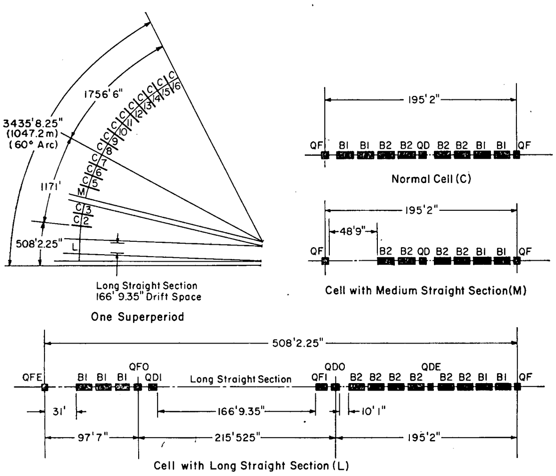


FIG. 2. Lattice of the main accelerator.

Aperture. The choice of aperture in the NAL design was determined largely by the need for room for extraction dynamics at full energy. The injection closed-orbit deviations are smaller and can also be decreased as experience is gained in operation.

The total length of bending magnets is approximately 15 500 feet, while the total length of focusing quadrupoles is approximately 1000 feet. It is, therefore, worthwhile economically to tailor the apertures of the bending magnets to fit the variations of β_x and β_z. It did not seem worthwhile to do this in the quadrupoles. We therefore have B1 magnets, with aperture 5 in. radially by 1.5 in. vertically, and B2 magnets, with apertures 4 in. radially and 2 in. vertically. The quadrupole apertures are 5 by 2 in.

Normal Cells. A normal cell, approximately 200 ft long, contains 2 quadrupoles and 8 bending magnets, 4 each of the two types, B1 and B2. There is a 7-ft ('mini') straight section after each quadrupole, so that the lattice order is

QFOB1B1B2B2QDOB2B2B1B1.

[Thus the B1's (B2's) which have larger radial (vertical) apertures, are on each side of the radially (vertically) focusing quadrupole, QF(QD), in which $\beta_x(\beta_z)$ is largest.] The 7-ft straight sections contain beam-sensing elements and correcting lenses, used to trim out remanent fields at injection and to drive the third-integral resonant extraction. The 1-ft ('micro') straight sections between magnets contain coil ends, vacuum bellows and joints, and pumpout ports.

Medium Straight Sections. A cell with a medium straight section is formed from a normal cell by omitting the first two B1 magnets. This, together with the 7-ft straight section, gives a drift space of almost 50 ft. This drift space will be used for beam-cleanup targets and the elements of the beam-abort system. The cell with medium straight section is the third cell downstream from the long straight section in each superperiod.

Long Straight Section. The first half of a normal cell is replaced by the sequence of bending and focusing magnets shown in Fig. 2. The total cell is 508 ft long, and the clear drift space is 170 ft. The special quadrupoles QFO, QFI, QDO, and QDI have the same cross section as normal-cell quadrupoles, but are made up of 4-ft and 7-ft sections, while the normal-cell quadrupoles are 7 ft in length.

One long straight section is utilized for the rf accelerating system. In our initial plans, separate long straight sections were utilized for injection and extraction. Later work showed that it was possible to combine these functions in a single location. This combination has advantages in requiring less expensive housings and in drawing together more functions for control purposes. Thus only two of the six long straight sections are utilized; the remainder are available for future expansion.

Magnet Design and Construction

Cores. An extensive computation and modeling program was carried out to determine the pole shapes of the bending magnets and quadrupoles because of the desire to keep the field shapes within specified limits up to the highest fields. The bending-magnet gradients k are within ± 0.01/m inside apertures of ± 1 in. up to 22.5 kG, which corresponds to 500 GeV. Instead of making the quadrupoles accurate up to 500 GeV, we have chosen instead to operate at the reduced ν-value discussed above. The extensive use of computation has made it possible to reduce the cross sections of the magnets while keeping the field shapes within limits up to high fields. Figure 3 shows the three kinds of main-accelerator magnets.

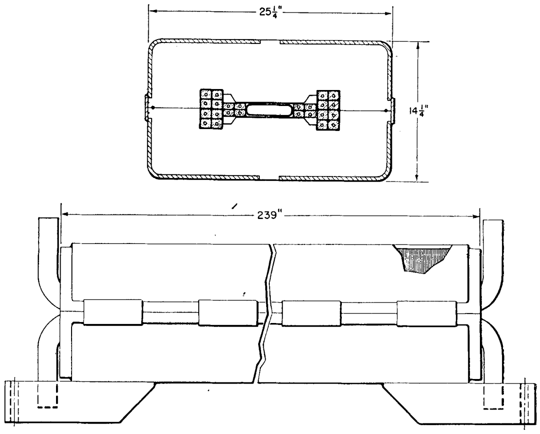
The core laminations are stamped from 0.060-in. low-carbon steel. Half cores are stacked (on a-precambered stacking table to reduce the sag of a mounted magnet) and the angle plates and end plates, which can be seen in Fig. 3, tack-welded to hold the core together.

We are not shuffling laminations to make the magnets uniform, but are placing completed production magnets around the ring according to their measured magnetic fields. The inventory of completed magnets that must be on hand at any one time presents a considerably smaller storage problem than would the inventory of laminations needed for a shuffling process.

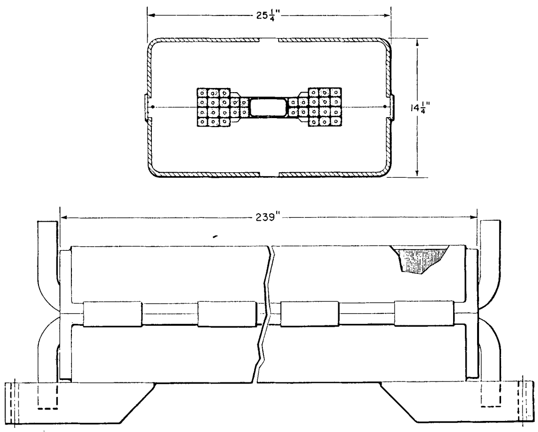
The production of magnet cores has been an easier job than we had thought. The problems that have had to be solved have been in the magnet coils.

Coils. The bending-magnet coils have turns both in the gap and in more conventional coil windows. Because they are close to the good-field region, the gap coils have tight tolerances on straightness and on vertical alignment of the upper and lower turns. During the modeling program, vendors had great difficulty in meeting these tolerances. It was decided to solve this problem by splitting the coil into an inner (gap) coil and upper and lower outer coils. We are fabricating the inner coils ourselves in a rented building near the site in order to meet the required tolerances. For the inner coils, straight (nonrolled) copper bars are used. Our production of inner coils more than keeps abreast of the production of outer coils, which is being carried out by vendors both in the United States and abroad.

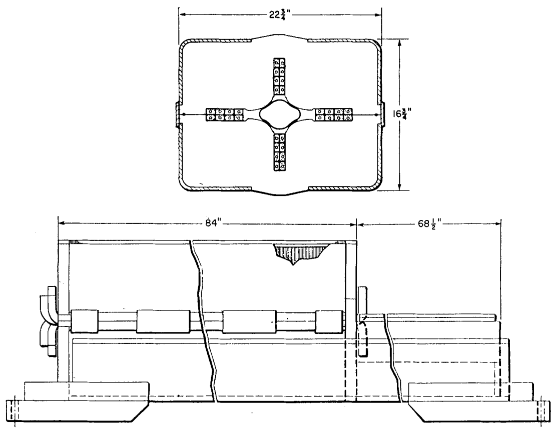
Magnet Assembly. An outer coil is bonded to each half-core. Then the inner coil and vacuum-chamber segment are bonded in the lower half and the two halves joined. They are held together by steel tabs welded to the angle plates, as shown in Fig. 3.



(a) B1 bending magnet.



(b) B2 bending magnet.



(c) Quadrupole magnet.

FIG. 3. Main-accelerator magnets.

More details of the magnet-fabrication procedure are given in Ref. 12.

Vacuum System

The vacuum envelope is made of stainless steel, of roughly rectangular cross sections in the bending magnets and elliptical cross sections in the quadrupoles. It is an all-metal system with welded joints. The high-vacuum pumping system utilizes small ion pumps mounted on the magnets. The roughing system utilizes mechanical pumps and diffusion pumps located in the service buildings around the ring. Sector valves are located to isolate the long straight sections.

Magnet Power Supply

The basic magnet power supply utilizes controlled-thyristor rectifiers in two-loop series circuits, with separate supplies for the bending magnets and quadrupoles around the ring. The power supplies are distributed around the ring in 24 service buildings.

What is unusual about the power supply is that there is no local energy-storage system. Instead, the Commonwealth Edison Company's power network is used as a storage system. NAL will pump energy from the network during the rise of the guide field and pump it back during the fall of the field (with, of course, careful attention to metering). This kind of energy storage has been investigated by Fox[13] and Rohrmayer[14] and was used at NIMROD after a generation failure, so is not unique to NAL. The effect on the power system during 200-GeV operation has been investigated in collaboration with Commonwealth Edison and found to be acceptable.

It was planned originally to install bus bars and water cooling for the full 500-GeV capability inside the tunnel but power supplies in the service building for only 200 GeV. Thus a later increase to 500 GeV could be accomplished just by the addition of power supplies, with no changes inside the tunnel to cause significant interference with operation. More recently, we have found that advances in the technology of thyristors have made it possible for us to procure power supplies adequate for 500 GeV (at a correspondingly slower cycling rate) at the cost originally estimated for 200 GeV. We have, therefore, proceeded with the full 500-GeV supply. Design work on the added cooling system is still in progress, as are investigations of the effect on the power network. Probably some local energy storage will be needed for continuous 500-GeV operation.

Main-Accelerator Tunnel

Considerable effort has been spent on the main-accelerator tunnel, because it is a structure almost 4 miles in length, and a small difference in the cost per unit length can therefore make significant differences in the total cost of the project. A completed portion of the main-ring tunnel is shown in Fig. 4.

Except for the Transfer Hall, at the position of the long straight section where injection and extraction take place, and the rf straight section, the entire circumference is made of horseshoe-shaped prefabricated concrete sections. These sections are sealed to a concrete floor-slab cast in an excavated trench. The maximum height in normal sections is 8 ft, and the maximum width is 10 ft. The magnet ring is placed close to the outer-radius wall, and the power and water lines are suspended over the magnets, so that approximately 7 ft of the width is clear space, used for electric vehicles for installing and servicing the ring. These dimensions might sound small to some, but we have found the clear space to be ample. In fact, if we were doing it again, we would probably make it smaller.

The maximum dimensions are enlarged from 10 by 8 ft to 12 by 9 ft at the long and medium straight sections for a possible later use, and at the locations of the stairways to the above-ground service building for piping bends and junctions. We have not attempted to make more provision for possible later extensions, because we believe it would be less expensive to modify the tunnel then than to include provisions now for many options about which we have little or no information.

The Transfer Hall and RF Building are special structures designed for the technical equipment to go in them. In each case, there are galleries above ground for the power supplies for this equipment.

There is no pile or caisson system. The magnet bases rest directly on the floor slab. The slab itself is founded on a firm glacial till underlying the site. Settlements are estimated to be of the order of one inch over many years, mostly within the first year. We should note that the flat-field bending magnets are quite insensitive to position errors.

Survey System

Alignment tolerances for the bending magnets are entirely different from those of the quadrupoles.

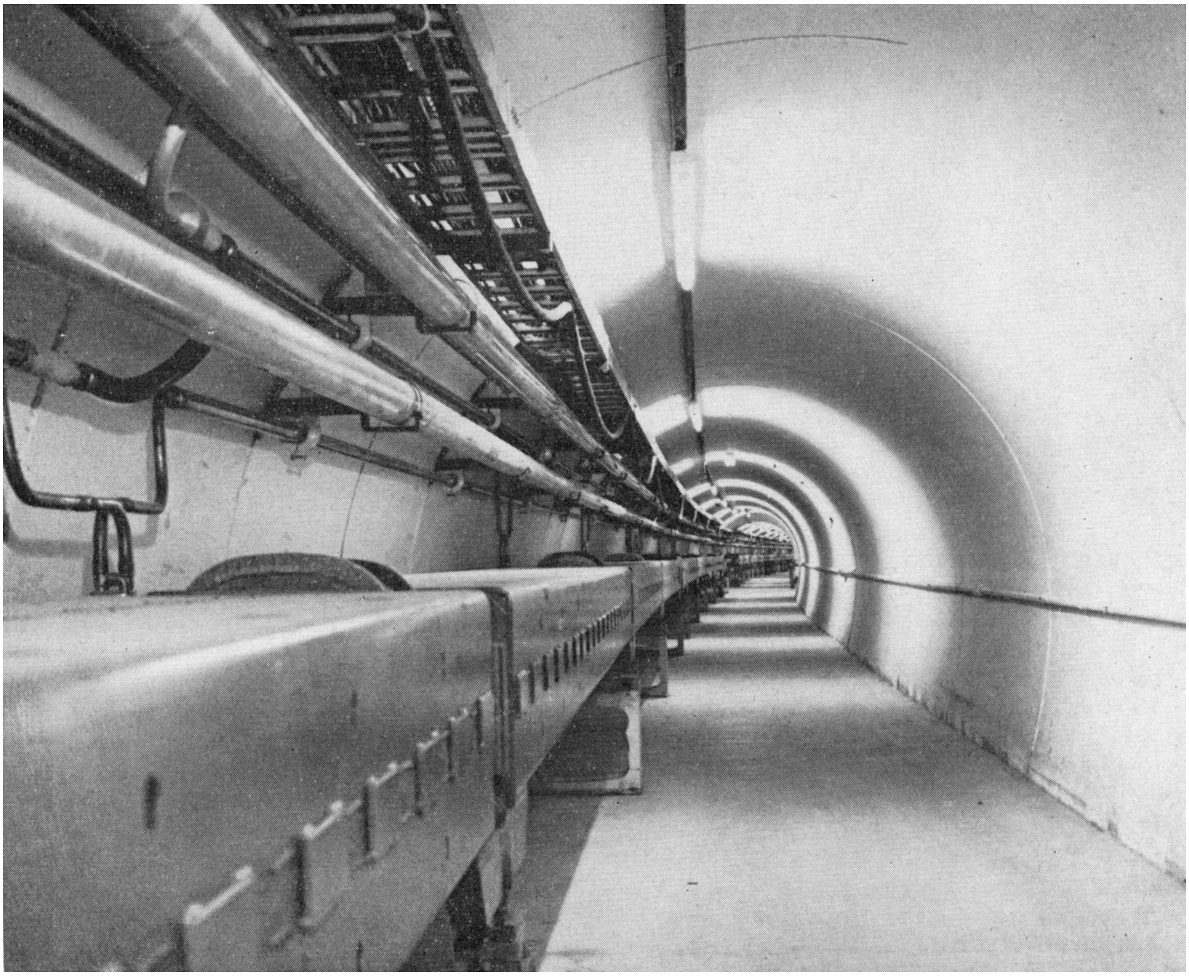


FIG. 4. Main-accelerator tunnel, looking downstream.

Because of their flat fields, the bending magnets are very insensitive to position errors, but are quite sensitive to twists. The major job is, therefore, leveling them, which is done by standard techniques.

On the other hand, the quadrupoles are very sensitive to position errors. A survey system has been developed using a laser beam to sight two quadrupoles away and measuring offsets from the intermediate quadrupole. There is also a system for sighting from the center of the ring for construction, but this system is not part of the fine survey.

RF System

The main-accelerator rf system must provide an energy gain of 2.6 MeV/turn for acceleration and a peak voltage of 3.5 MV/turn for phase stability. The frequency-modulation swing is only 0.55 per cent because of the 8-GeV injection energy.

The system to meet these requirements is a 16-cavity ferrite-tuned system operating at approximately 53 MHz. Thus in normal operation each cavity has a peak voltage of approximately 200 kV, but the system can also be operated with only 14 cavities, with each at higher voltage. The cavities operate independently, except that they have a common input from the beam-control system. The final power-amplifier stages are mounted on the cavities in the tunnel, while the ferrite-bias tuners, anode supplies, modulators, and low-level stages are in the gallery above. There is a high degree of commonality of components between the main-accelerator and booster rf systems, even though their frequency modulation ranges are very different.

There are three comments of interest about the design. First, the power extracted by the beam is significant, and beam loading must be considered. Second, the system must provide holding and synchronizing voltages during injection; since it must be able to treat individual booster pulses differently, it must be able to respond rapidly in phase and amplitude. Third, gaps in the beam, where energy is not extracted from the cavity, must also be handled by the system.

The methods of dealing with these problems are beyond the scope of this report, but are discussed in Ref. 3.

4. BOOSTER

The booster is a single-purpose accelerator whose only function is to inject into the main accelerator. Suggestions have often been made that its beam could be used for physics research during the 80 per cent of the total time that it is not in use as an injector. But this use would not be without cost, because experimental facilities would be needed. In addition, many accelerators have been operating in this energy range for a number of years, and it is difficult to believe that the booster could be a significant addition to these capabilities.

The booster is also quite large (approximately 75 m equivalent radius). It would be possible to design a smaller-radius 8-GeV booster, but if it were smaller, more booster pulses would be needed to fill the main ring, and the repetition rate would have to be increased to keep the injection time constant. Thus there is no strong urge in the design to decrease the radius. The considerations of maximum attainable peak guide field that were important in the main-accelerator design are therefore not relevant in the booster; the argument for separated-function magnets is therefore less strong. Both separated and combined-function systems were considered in the design and the combined-function system chosen, because it has a smaller number of types of major components.

Lattice

The booster is a combined-function synchrotron with a FOFDOOD lattice. This lattice type was chosen because it gives a beam more nearly circular in cross section in the rf cavities, which are located in pairs in the 20-ft straight sections between D magnets.

There is concern in a rapid-cycling accelerator of the booster type that the number of synchrotron oscillations per revolution ν_s becomes quite large shortly after injection which can give serious coupling problems between betatron and synchrotron oscillations. In the booster as designed, the maximum value of ν_s is 0.075, small enough that coupling should not be a problem.

Magnet System

The F and D magnets have different pole shapes, tailored to fit the variations of the amplitude functions β_x and β_z. The poles also have a small sextupole component to cancel (in first order) the variation of betatron wave numbers with revolution (this is not a new feature—the CEA magnets have sextupole components for the same purpose).

The magnets are stacked from one-piece 0.025-in. silicon-steel laminations on a curve corresponding to the bending radius. The coils are wound separately of 0.46-in. square hollow copper bars, then inserted into the magnet. A stainless-steel vacuum envelope is wrapped around the magnet assembly; the entire magnet structure is then resin-bonded to make the assembly, using an inflated rubber bag to keep resin off the poles.

Thus the vacuum envelope is outside the magnet and the coil, as in the 10-GeV Cornell Electron Synchrotron. This system required a considerable development effort to make it meet the vacuum requirement of 5×10^{-7} torr average pressure. But the development has been successful, and the gains are considerable. An inner vacuum chamber in a rapid-cycling synchrotron must be nonmetallic to reduce eddy currents. It is not only costly to fabricate, but takes up considerable vertical aperture, which is reflected in a larger cost for the stored energy of the magnet system. Our use of an outer vacuum chamber makes it possible to mount the chokes and capacitors of the energy-storage system on a girder with an F and a D magnet, forming an integral module. Since these components are in the tunnel, it has been possible to reduce the amount of gallery space above the tunnel, a further reduction in cost. Figure 5 is a photograph of the interior of the completed booster tunnel, with magnet girders installed. More details of the magnet fabrication are given in Ref. 15.

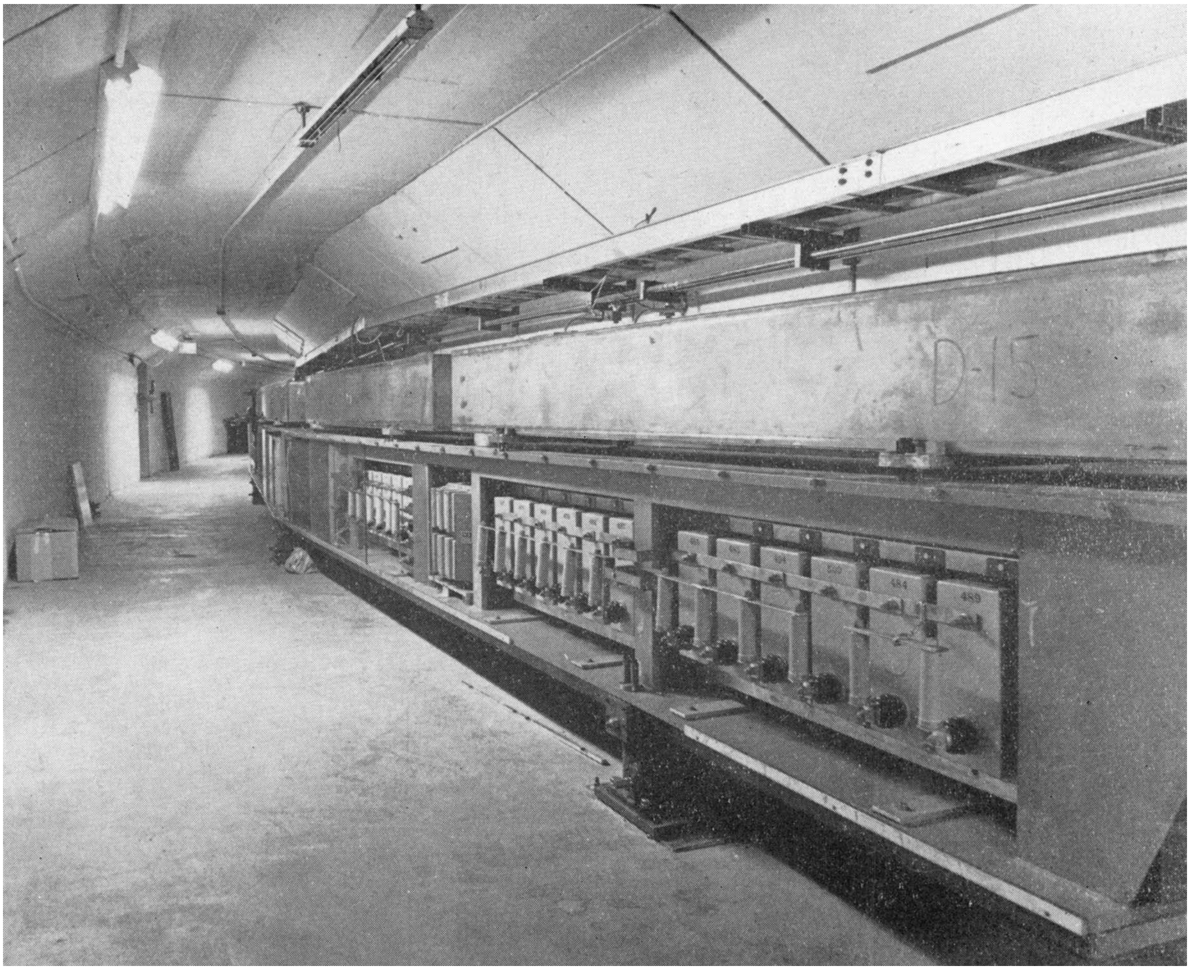


FIG. 5. Booster tunnel, looking upstream. The boxes marked 'D15' and 'F12' are magnets. Under them on the girder are capacitors and a vacuum pump. The choke is at the far end of the girder.

RF System

The main components now installed in the galleries are the power supplies for the rf system. The power amplifiers, which are the same as those of the main-ring system, are mounted on the 16 cavities. The booster rf is a ferrite-tuned system like the main accelerator, although, of course, its frequency-modulation swing is much larger (1.76 to 1). Beam is injected from the linac with the rf off and is then bunched adiabatically to avoid particle loss.

5. CONTROLS

The primary goal of the design of our control system is that one operator should be able to carry out all routine control functions on the accelerator. There are, of course, large numbers of monitoring and control functions just because of the size of the accelerator. The single operator will perform his monitoring and control functions with the aid of a computer, which will communicate with elements of the system through a multiplex system and a number of smaller ('mini') computers. Although the central computer is important for smooth and efficient operation, we do not want operation to be completely dependent on it, and there is a system for monitoring more directly and introducing control commands manually into the minicomputers. This system may be awkward in practice, but it will make operation without the central computer possible.

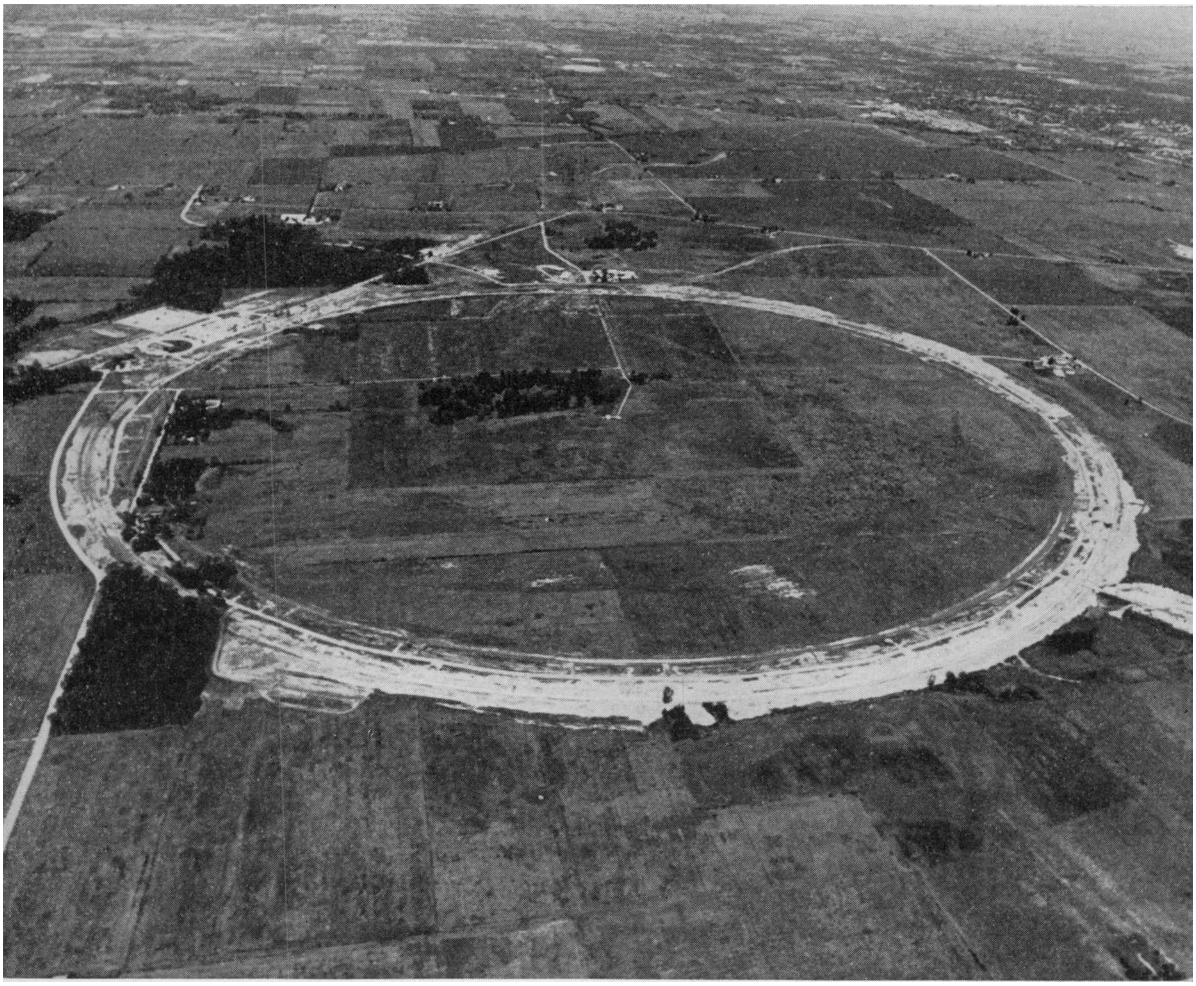


FIG. 6. An overall aerial view of the site, looking north. The linac and booster are at the left on the northwest corner of the ring. The road going northeast from the booster area parallels the external beam line. Part of the Laboratory Village can be seen at the extreme right.

The development in 'small' computers in the last few years can only be described as enormous. The use of one of these new systems allows great flexibility in operation and extremely rapid collection of data. Some of the rapid measurements pertaining to the Cockcroft-Walton and linac are discussed in Ref. 4.

6. EXTRACTION AND EXPERIMENTAL AREAS

The accelerated beam can be extracted from the main accelerator either in one turn (20 microseconds) or slowly over a flattop (up to 1 second at 200 GeV, correspondingly longer at higher energy). The most important element of the extraction system is the electrostatic septum developed by Maschke.[9] The device uses thin wires as the inner electrode of a transverse electric field. This electrode can be made much thinner than the current-carrying septum of a magnetic deflector and, consequently, the particle losses on it are much smaller.

After extraction, the proton beam is transported down a tunnel to a splitting station, where all or part of it can be bent toward different experimental areas by devices very similar to the extraction system.

The experimental areas are somewhat more special-purpose than many of those in present-day

FIG. 7. The injection area, looking southwest. The view is down the linac building at the right. The booster is beyond, with a utility plant and cooling pond within its circumference. The Cross Gallery, which contains the control room, is between us and the booster. The main accelerator is at the left, with the Transfer Hall under the berm just east of the buildings.

accelerators. Straight ahead along the extraction line is the Neutrino Area with a long earth shield. A 15-ft bubble chamber is being constructed beyond this shield. To the north of the Neutrino Area I is the Meson Area, designed primarily for electronic detectors. When the initial operating energy was changed from 200 to 500 GeV, it was decided to leave the Meson Area as a 200-GeV area in order not to delay its construction. In contrast, the Neutrino Area is being redesigned as a full 500-GeV area. (A third area, to the south of the Neutrino Area will be a 500-GeV electronic-detection area; it is in the early stages of design.)

7. CONSTRUCTION STATUS

At the time of writing this report (October, 1970), we are working toward completion of the accelerator. The status of the accelerator systems can be summarized as follows:

(i) The Linac Building was completed and occupied at the beginning of 1970. All tanks and rf systems are on hand. Beam has been accelerated through 6 tanks to an energy of 139 MeV.

(ii) The Booster Tunnel and Galleries were occupied in the spring of 1970. Approximately half the booster magnets have been installed. The 139-MeV linac beam has been injected into the ring and transported around to extraction, where it has been taken out and sent to the main ring. Full-power tests have been made on one-half of the ring.

(iii) We are occupying more than half the Main-Ring Tunnel, including the Transfer Hall and the galleries above it. Approximately 300 magnets have been completed and are being installed in the tunnel.

(iv) Construction is under way on the beam-line housing to the Meson Area. Many utility systems and the first phase of the Central Laboratory are also being constructed.

Figures 6 and 7 are aerial photographs showing the status of construction.

It is appropriate here to add a few words about the procurement methods used. We have frequently gone out for bids on conventional structures in several phases, enabling the work to start earlier on the first phase. We have also made use of options for parts of the work and have on some occasions given incentive contracts to speed work on structures needed to maintain the schedule.

On technical components, we have often split contracts between several vendors, leaving options for the remainder of the work with each. Who gets the option is determined by performance. In some cases, we have also built a part of the components ourselves, which has provided guidelines for private vendors. All these methods have helped to keep to the very tight schedule and have produced satisfactory products.

ACKNOWLEDGEMENTS

This paper has reported the work of many devoted people on the NAL staff who have made contributions to the design and construction. It is an honor to report for them. I have also reported on the work of DUSAF, our architect-engineer-management firm, who have added greatly to the project in many ways, and I acknowledge with gratitude their splendid work.

REFERENCES

1. 200-BeV Accelerator Design Study, University of California Lawrence Radiation Laboratory, Report UCRL–16000, June, 1965.
2. Report on the Design Study of a 300-GeV Proton Synchrotron, CERN Report AR/Int. SG/64–15, November 1964.
3. National Accelerator Laboratory Design Report, January 1968.
4. C. D. Curtis *et al.*, *Particle Accelerators* **1,** 93 (1970).
5. R. R. Wilson, Electron Synchrotrons, *Handbuch der Physik XLIV*, **171** (1959). See especially the end of Sec. 3 on p. 175.
6. M. Sands, Ultra High Energy Synchrotrons, Midwestern Universities Research Association Report MURA–465, June 10, 1969 (unpublished).
7. W. Hardt, Proc. Sixth Int. Conf. on High Energy Accelerators, 1967, p. 320. Cambridge Electron Accelerator Report CEAL–2000.
8. T. L. Collins, Long Straight Sections for AG Synchrotrons. Cambridge Electron Accelerator Report CEA–86, July 10, 1961 (unpublished).
9. A. W. Maschke, Proc. Seventh Intern. Conf. on High Energy Accelerators, 1969, Yerevan, Armenia, USSR (to be published).
10. M. G. White, Preliminary Design Parameters for a Separated-Function Machine, Princeton Internal Report, March 3, 1953 (unpublished).
11. T. Kitagaki, *Phys. Rev.* **89,** 1161 (1953).
12. H. Hinterberger and R. Sheldon, Proc. Intern. Conf. on Magnet Technology, 1970, Hamburg, Germany (to be published).
13. J. A. Fox, A Review of Static Power Supply Alternatives for the 300-GeV Accelerator Magnet System, Rutherford Laboratory Report E/PS-DS/300 GeV/ JAF–2, December, 1967 (unpublished).
14. A. Rohrmayer, *IEEE Trans. Nucl. Sci.* **NS–14,** No. 3, 849 (1967).
15. R. Billinge *et al.*, Proc. Intern. Conf. on Magnet Technology, 1970, Hamburg, Germany (to be published).

Received October, 8 1970